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Interactive effects of ionizing radiation and climate change on the abundance of breeding birds

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ABSTRACT

The effects of ionizing radiation on living beings have been studied under lab conditions and in the field. The first approach may often lack in realism, while the second may lack rigorous experimental approaches. Because ionizing radiation may interact with other stressors such as heavy metals and climatic conditions, it is difficult to assess the independent effects of such different factors. We conducted extensive breeding bird surveys at Fukushima during 2011–2017 and related the abundance of different species to the ambient level of radiation. Climate warming has affected many parts of the globe suggesting that the effects of ionizing radiation at Fukushima may interact with precipitation and temperature. We assessed the independent and the interacting effects of temperature, precipitation and ionizing radiation for the abundance of breeding birds at Fukushima. We documented strongly negative effects of ionizing radiation on the abundance of 32% of bird species as found in previous studies while 5% would be expected by chance. The main effects of temperature and radiation affected 21% of the species, while the interaction effects of temperature by radiation affected 19%, and the interaction effect of precipitation by radiation only accounted for 8%. While the effects of temperature were significant, similar tests for precipitation effects were not statistically significant. The effects of ionizing radiation on adults was strongly positively correlated with the effects of ionizing radiation on juveniles. These findings imply that the main effects of ionizing radiation were considerable, they were much larger than those of temperature and precipitation, and the interaction effects of temperature and ionizing radiation were significant. The effects on adults was comparable to the effects on juveniles. This first study of interactions between two stressors, ionizing radiation and climate, suggests that it is unlikely that the effects of confounding variables account for the apparent effects of ambient ionizing radiation on bird populations at Fukushima.

1. Introduction

Radiation hotspots with naturally occurring, high levels of ionizing radiation are widespread across the world (Møller and Mousseau, 2013). Such naturally occurring radiation has levels of radioactive contamination with negative consequences for plants, animals and humans alike. The largest source of anthropogenic radiation across the globe stems from nuclear accidents and atomic bomb tests followed by nuclear accidents in Chernobyl and Fukushima being by far the largest accounting for the equivalent of > 12,000 PBq and > 1850 PBq of total radioactivity, respectively (Lelieveld et al., 2012). These releases of ionizing radiation had significant effects on the diversity and the abundance of organisms, but also on the condition and health status of the organisms, including humans at these sites.

There is extensive evidence of negative effects of ionizing radiation on the condition and well-being of free-living organisms and humans living in or near accident areas (e.g. Møller et al., 2005; Yablokov et al., 2009; Møller and Mousseau, 2007, 2011, 2013; Hiyama et al., 2012; Møller et al., 2012, 2013; Murase et al., 2015; Okano et al., 2016; Otaki, 2016). Such correlational evidence of negative effects of ionizing radiation on organisms is potentially confounded by other variables that were released at the same time as radionuclides. These include evacuation of contaminated areas in Chernobyl and Fukushima for humans, but also the confounding effects of heavy metals and other substances from nuclear reactors during accidents. For example, Chernobyl has high levels of contamination with lead, cupper and many other metals, and such metals may have negative effects on the reproductive success and survival of living beings (Yablokov et al., 2009). In addition, helicopters dumped at least 2400 t of lead, but perhaps as much as 6720 t (Nesterenko, 1997), into the Chernobyl reactor during attempts

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to stop the fire (Nesterenko, 1997; UNSCEAR, 2000; Samushia et al., 2007; Yablokov et al., 2009). This resulted in high levels of contamination in the surrounding region.

It is not only contaminants that may affect organisms in Chernobyl and Fukushima, but the mere absence of humans may reduce or eliminate disturbance effects (Samia et al., 2015). Humans have abandoned contaminated areas in Chernobyl and Fukushima as a consequence of evacuations, and the absence of humans may have positive effects on large mammals such as wolf *Canis lupus*, red deer *Cervus elaphus* and roe deer *Capreolus capreolus* (Deryabina et al., 2015) due to reduced hunting pressure. However, it seems unlikely that the abundance and diversity of small birds, reptiles, amphibians, insects and spiders have been positively impacted by such evacuations.

Many field studies linking the abundance of organisms to the level of ambient radiation have shown negative associations (reviewed in Mousseau and Møller, 2014). Most studies have relied on correlational evidence that assumes that the level of ionizing radiation at a given set of sites is not confounded by additional unmeasured variables (e.g. other stressors like heavy metals or environmental conditions such as increased temperatures and precipitation linked to recent climate change). Since both the Fukushima and Chernobyl sites have highly heterogeneous distributions of radionuclides (Shestopalov, 1996; Mousseau and Møller, 2014), it seems particularly unlikely that other stressors have played a significant role in the interactive effects of the impact of ionizing radiation on the abundance and the species richness of organisms. That would particularly be the case if locations of sites for assessment of species richness and abundance have been chosen randomly in such field studies.

Although it seems unlikely that ionizing radiation will be consistently distributed in a way that would bias any research based on randomly chosen study sites, it would still be interesting to investigate the independent and the interactive effects of ionizing radiation and other variables such as climatic conditions. If two or more variables simultaneously impact species richness and abundance of organisms, we should expect a stronger impact on species richness and abundance of the different stressors. In other words, we should expect an interactive effect of the multiple stressors on species richness and abundance. We are unaware of tests for such interaction effects of the impact of ionizing radiation on the abundance of organisms. Here we provide such an example by testing for an interactive effect of multiple stressors.

The objectives of this study were to test (1) whether radiation effects are the main cause of reduced abundance of breeding birds in contaminated areas in Fukushima, even after controlling for potentially confounding effects of additional stressors (climate change); (2) whether the effects of ionizing radiation and climate change on the abundance of breeding birds interact; and (3) whether effect size for ionizing radiation on the abundance of juveniles was significantly positively related to effect size for the effects of ionizing radiation on the abundance of adult birds, as expected if the two measures of bird abundance were determined by the same factors across 400 bird survey points (Garnier-Laplace et al., 2015). Such effects of radiation may be modified by other environmental factors (Garnier-Laplace et al., 2013; Mothersill et al., 2007; Deans et al., 2017). To this end we used extensive breeding bird surveys at Fukushima, Japan collected during 2011–2017. We did so by analyzing bird survey data for 48 species at Fukushima. Previous studies at Fukushima and Chernobyl have shown that population density and species richness of birds and other organisms is reduced, on average by as much as 50% in heavily contaminated regions (Møller et al., 2005; Møller and Mousseau, 2007, 2011; Yablokov et al. 2009; Hiyama et al., 2012; Møller et al., 2012, 2013; Murase et al., 2015; Okano et al., 2016; Otaki, 2016).

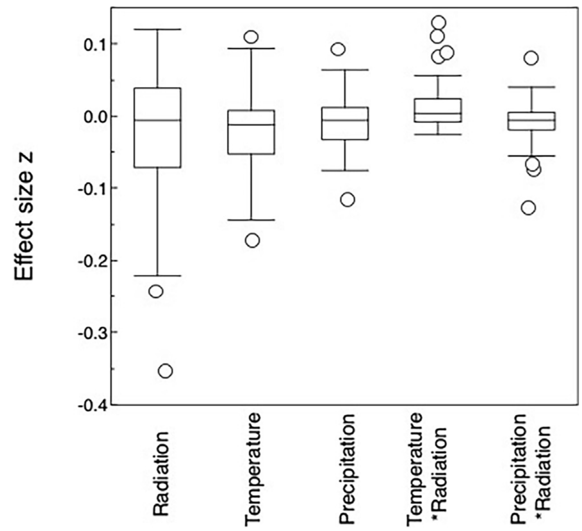

Fig. 1. Box plots of standardized effect sizes for five categories of birds at Fukushima. Box plots show medians, quartiles, 5- and 95-perecentiles and extreme values.

2. Methods

2.1. Study sites and survey methods

We surveyed breeding birds in the surroundings of Fukushima, Japan at a number of study sites located in open farmland and forested sites at altitudes ranging from 300 to 700 m (Garnier-Laplace et al., 2015; Fig. 1).

APM conducted breeding bird surveys during the first two weeks of July 2011–2017. A total of 300–400 survey sites were identified with GPS coordinates at a distance of 100 m between neighboring points. Each point count lasted 5 min during which we recorded all birds seen or heard (Blondel et al., 1970; Møller, 1983; Bibby et al., 2005; Vorısek et al., 2010). We also recorded weather (temperature, precipitation), cover with farmland and forest, presence or absence of humans and presence or absence of cars (Møller et al., 2015a,b).

We recorded the presence of nestlings or juveniles by determining whether adults were giving alarm calls when we approached a nest, when an adult was carrying food to offspring or when fledglings were seen. We made separate analyses of the relationship between the abundance of juveniles or adults separately were related to the level of background radiation. We subsequently quantified the relationship between abundance of juvenile or adult individuals, respectively, and the level of ambient background radiation. These analyses were made under the assumption that adults have been exposed to radiation for longer time than juveniles that have either only recently fledged or only recently moved to a site with contamination.

Ambient level of radiation was measured 3–5 times at each study site using a handheld Geiger counter at ground level. We measured radiation at each site each year separately to account for the fact that radiation levels changed over time either due to a reduction caused by the fixed half-life of isotopes, or because radioactive substances were transported among sites due to precipitation or caused by human traffic. We have previously shown that ambient radiation measured with a Geiger counter is strongly positively correlated with recordings from a radiation record device used at Fukushima (Møller et al., 2015a,b). Our measurements are also strongly positively related to recordings reported by citizen scientists involved in the Fukushima Monitoring project (Adapted from http://www.nnistar.com/gmap/fukushima, generated by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and local government (color figure online)). Finally, readings from the Geiger counter were strongly

Table 1
Effect size for radiation was significantly related to effect size for precipitation by radiation interaction, but not to the other three predictors. The model had the statistics $\chi^2 = 11.73$, df = 4, $P = 0.020$.

Term	Likelihood ratio χ^2	P	Estimate	SE
Intercept	1.13	0.29	−0.015	0.014
z Precipitation	1.93	0.16	−0.455	0.324
z Temperature	1.61	0.20	0.295	0.231
z Precipitation * z Radiation	5.71	0.017	1.030	9.418
z Temperature * z Radiation	1.43	0.23	−0.511	0.424

positively correlated with readings from thermoluminescent dosimeters (TLDs) (Møller and Mousseau, 2018).

We extracted data on temperature and precipitation for the main breeding season May-July from the Fukushima Meteorological Station, Fukushima, Japan. There is evidence of significant temporal change in temperature and precipitation during our study, implying that birds have been subject to different temperatures and levels of rainfall during the course of the present study which only lasted 2011–2017. These changes are even more pronounced when including weather during recent decades.

2.2. Statistical analyses

We estimated descriptive statistics for the variables of interest. We estimated the partial effects of the relationship between level of ionizing radiation, and temperature and precipitation and for the interaction between radiation and temperature and the interaction between precipitation and radiation, using GLM with pPoisson distributed count data. Likelihood ratio χ^2's were used to estimate effect sizes for each species and each of the five components in Table 1 and Fig. 1 as $z = \sqrt{((\chi^2)/N)}$, where z is the z-transformed Pearson product-moment correlation coefficient. We subsequently calculated mean and variance in effect sizes for each of the five component categories. We tested in a Welch ANOVA for unequal variances whether mean effect sizes were significantly different, and whether variances differed in a Levene's test.

We estimated effect sizes for level of ionizing radiation and abundance of juveniles and adults, respectively, for a total of 12 species of birds with both age classes present in the current study. All statistical analyses were done with SAS (2012).

3. Results

We surveyed breeding birds at 400 sites during 2011–2017 recording a total of 48 species of birds and 13,081 individual birds among the study sites. We documented high levels of variation in ambient ionizing radiation among survey points ranging from 0.07 to 205.90 μSv/h, mean (SE) 5.43 μSv/h (0.18). Both temperature and rainfall (temperature range 19.4–21.9 °C, mean (SE) 20.86 °C (0.86); precipitation 70.5–195.5 mm, mean (SE) 109.1 mm (0.9) also varied significantly among years, showing that birds were exposed to different environmental conditions in different years.

Mean effect size estimated as the z-transformed Pearson product-moment correlation coefficient for the number of bird species and the relationship with radiation was intermediate at $z = -0.313$, $P < 0.001$). For the number of birds and radiation mean effect size was large at −0.426, $P < 0.001$. Mean effect size for temperature and number of species was $z = -0.103$, $P < 0.0001$ and for number of birds −0.158. Effect size for precipitation and number of species was $z = -0.108$, $P < 0.0001$ and for number of birds −0.158. Effect size for temperature and radiation was $z = 0.074$ for species richness and for number of birds $z = 0.121$. Effect size for precipitation and radiation was −0.047 for species richness and for number of birds −0.107.

A Welch ANOVA for unequal variances showed significant differences among means (Fig. 1; $F = 5.28$, df = 4, $P = 0.0006$) and a

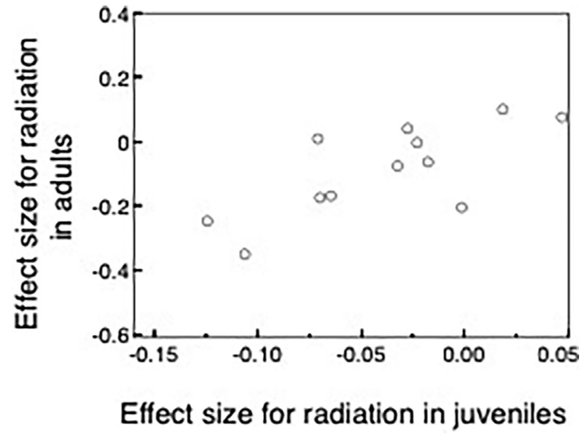

Fig. 2. Standardized effect size for the relationship between level of ionizing radiation and abundance of juvenile and adult birds, respectively, for a total of 12 species of birds at Fukushima. The statistical analysis accounting for this relationship was $\chi^2 = 9.31$, df = 1, $P = 0.0011$.

Levene's test showed a difference in variances among categories of effect types ($F = 15.80$, df = 4, 235, $P < 0.0001$). The effect size for the interaction between July temperature and radiation was statistically significantly different from effect size for the interaction between July precipitation and radiation (Fig. 1; $z = 2.74$, $P = 0.0061$). The effect size for radiation was significantly different from the interaction between July temperature and radiation ($z = 2.13$, $P = 0.033$). The effect size for temperature was significantly different from the interaction between July temperature and radiation ($z = 3.12$, $P = 0.0018$). The effect size for precipitation was significantly different from the interaction between July temperature and radiation ($z = 2.35$, $P = 0.018$).

Effect size for radiation effects on abundance of adult birds was positively correlated with effect size for radiation effects on abundance of juvenile birds of the same species (Fig. 2; LR $\chi^2 = 9.31$, df = 1, $P = 0.0023$, estimate (SE) = 2.070 (0.552)). While effect sizes ranged from −0.353 to 0.098 in adults, or a variance of 0.114, it ranged from −0.124 to 0.047 in juveniles, or a variance of 0.0025. This implies a variance ratio of 45.55, which is significant at the 0.001 level for df = 11, 11.

4. Discussion

Ambient ionizing radiation was consistently negatively correlated with species richness and abundance of breeding birds, while there were very weak correlations with temperature and precipitation at Fukushima, Japan during 2011–2017. Likewise, there were very weak interactions between ionizing radiation and temperature and precipitation, respectively. This means that radiation in combination with temperature and precipitation only had very weak effects on species richness and abundance of birds. Finally, effect sizes for radiation in adult birds were strongly positively correlated with effect sizes for juveniles, suggesting that effects of radiation were similar in the two age classes.

Climate change is a widespread and real phenomenon affecting numerous organisms across the world (Stenseth et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003; Møller et al., 2004, 2010). Scientists have reached a consensus concerning the generality of such effects making it highly likely that this is a real phenomenon rather than a "fad" (Anderegg et al., 2010; IPCC, 2018). The findings reported here suggest that it is likely that studies reporting an impact of factors other than climate change can show an impact of such additional effects even after partialling out the effects of climate change. Thus the confounding effects of climate change will tend to be stronger than the effects of other variables. In other words, the effects of ionizing radiation will be particularly strong once the effects of climate change have been

accounted for. Here we showed much weaker effects of climate change, as revealed by temperature and precipitation, than of ionizing radiation. It has been suggested by us (e.g. Mousseau and Møller, 2017) and by others (e.g. Garnier Laplace et al., 2013) that the apparent higher-than-expected sensitivity of organisms living near Chernobyl could reflect the combined impacts of multiple stressors that are rarely examined simultaneously when conducting controlled laboratory or enclosure studies that were typical of studies employed to test radiosensitivity in the past (e.g. Thompson, 1989). Although it seems likely that a variety of radionuclides (e.g. I-131, Sr-90, Cs-134, Cs-137, Pu-239) and other heavy metals might have dispersed in similar manner at the time of accident, stressors related to climatic conditions would be not be expected to covary with radionuclide distribution. This is especially likely given the landscape scale of the accident (more than 190,000 km of significant contamination across Europe; IAEA, 2006) and so it would be interesting to investigate the independent and the interactive effects of ionizing radiation and other variables such as climatic conditions. Climate change is a widespread and real phenomenon affecting numerous organisms across the world (Stenseth et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003; Møller et al., 2004, 2010). Scientists have shown a consensus on such general effects making it highly likely that this is a real phenomenon rather than a fad (Anderegg et al., 2010). These findings also make it likely that studies reporting an impact of other factors than climate change will show an impact of such additional effects even after partialling out the effects of climate change. Thus the confounding effects of climate change will tend to be stronger than the effects of other variables. In other words, the effects of ionizing radiation will be particularly strong once the effects of climate change have been accounted for. Here we showed much weaker effects of climate change as revealed by temperature and precipitation than of ionizing radiation.

We surveyed both juvenile and adult birds at Fukushima, by relying on the fact that adults giving alarm calls at their nests have dependent offspring, just as adults with food in their beak and independent fledglings able to fly could be considered reliable information on breeding. If the same factors accounted for the abundance of both juveniles and adults, we should expect standardized effect sizes for juveniles and adults to be strongly positively correlated. That was indeed the pattern that we found. This suggests that it is the same factors that account for and limit the abundance of these two age classes. We are unaware of any previous study that has used this simple prediction to test for an effect of one or more stressors, as in the present case of ionizing radiation.

This study implies that there are straight forward ways of studying interactive effects of stressors on organisms. If two or more factors are studied for their impacts on a population of animals, we can rank these factors relative to their importance by relying on standardized effect sizes, as in the present study. Here we have shown that there are only weak and marginally significant interaction effects on the effects of ionizing radiation. This finding is important because it suggests that the effects of ionizing radiation exceed these main and interaction effects. If this prediction is valid, we can dismiss the hypothesis that confounding effects are responsible for the patterns observed.

While this paper deals with interaction effects between different stressors at Fukushima, this does not suggest that we cannot adopt a similar approach when addressing questions of multiple stressors. There are also some general applications because studies of ecotoxicology often test effects of pesticides and other substances by using a single substance at a time. In contrast, “cocktail” effects are often common or even predominant suggesting that interaction effects may be much common that usually assumed. The weak interaction effects and the predominant main effects of radiation in this study may thus be the exception rather than the rule.

Ionizing radiation has been shown to have broad and extensive negative effects on living organisms (e.g. Møller et al., 2005; Møller and Mousseau, 2007, 2011; Yablokov et al., 2009; Hiyama et al., 2012; Møller et al., 2012, 2013; Murase et al., 2015; Okano et al., 2016; Otaki, 2016). This point of view has been challenged by claims that other stressors such as climate and the presence of humans on their own or in combination negatively impact the diversity and the abundance of animals. Such hypotheses require carefully designed experiments that can distinguish among alternatives. In the present study, we have shown very weak effects of interacting factors. This does not suggest that other stressors do not have negative effects that become exacerbated by the action of multiple stressors. Clearly, we need additional experimental studies to allow discrimination among these hypotheses.

While interactions between different stressors have been hypothesized to impact populations of organisms more severely, we found little support for this suggestion. In contrast, we found a strong main effect of ionizing radiation that accounted for most of the negative fitness consequences of such nuclear accident.

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Permits

No permits were required for this study.

Author declaration

APM got the idea behind this study. APM made the statistical analyses. TAM and APM obtained funding and wrote the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2018.12.031.

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